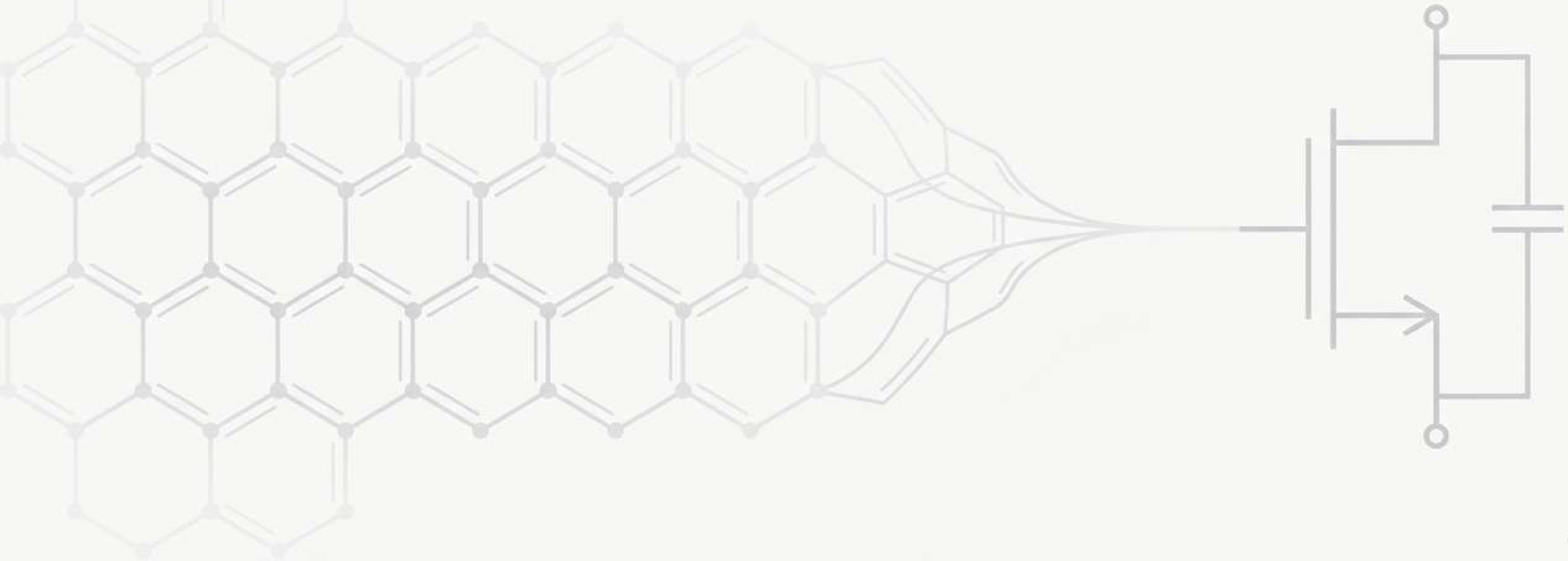
Beyond Silicon: Unlocking Sub-5nm Transistors with 2D Layered Materials

An investigative journey from theoretical promise to a 1-nanometer experimental breakthrough.



The semiconductor industry is approaching a fundamental scaling wall

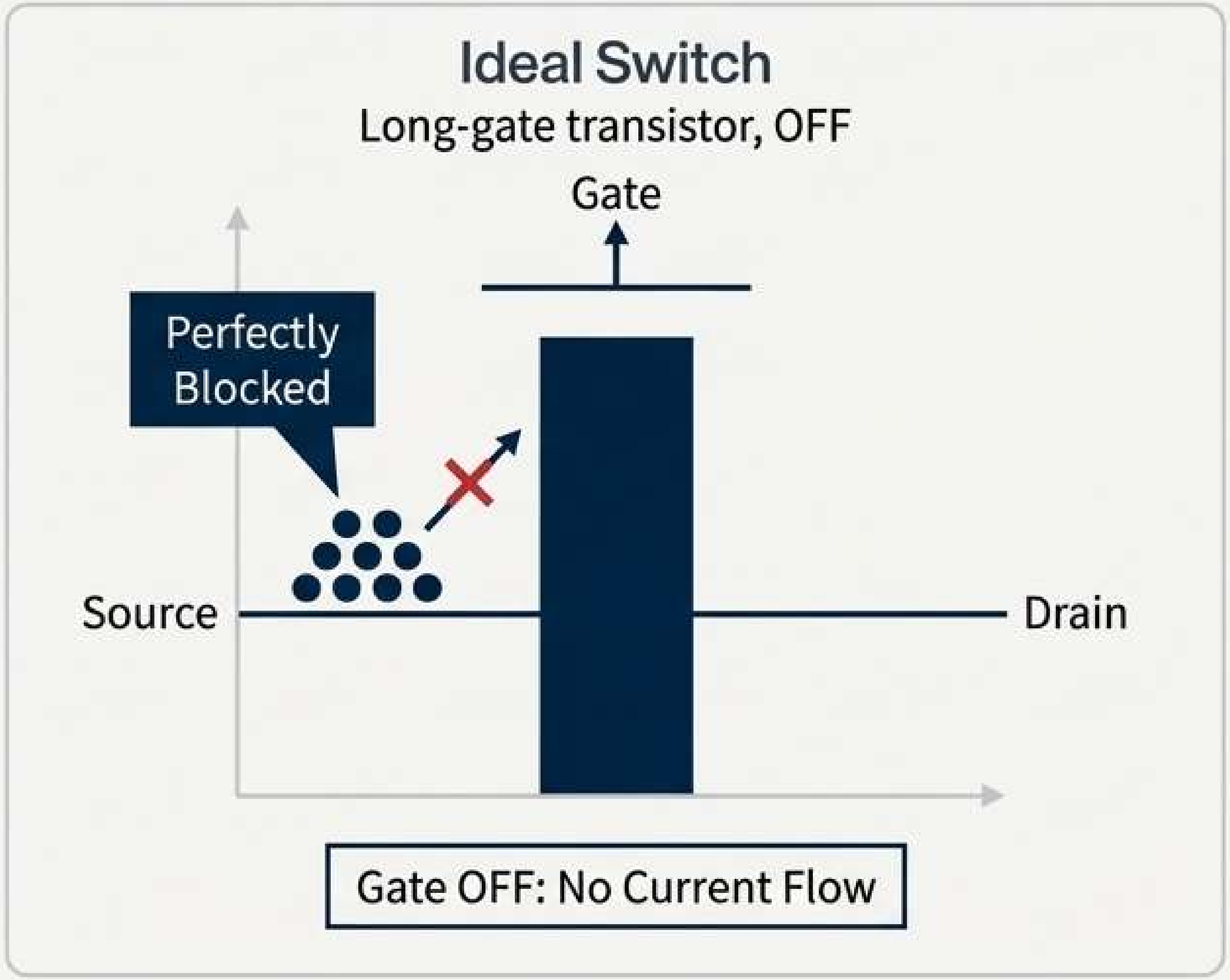
Today's state-of-the-art transistors have a gate length of approximately 15 nanometers.

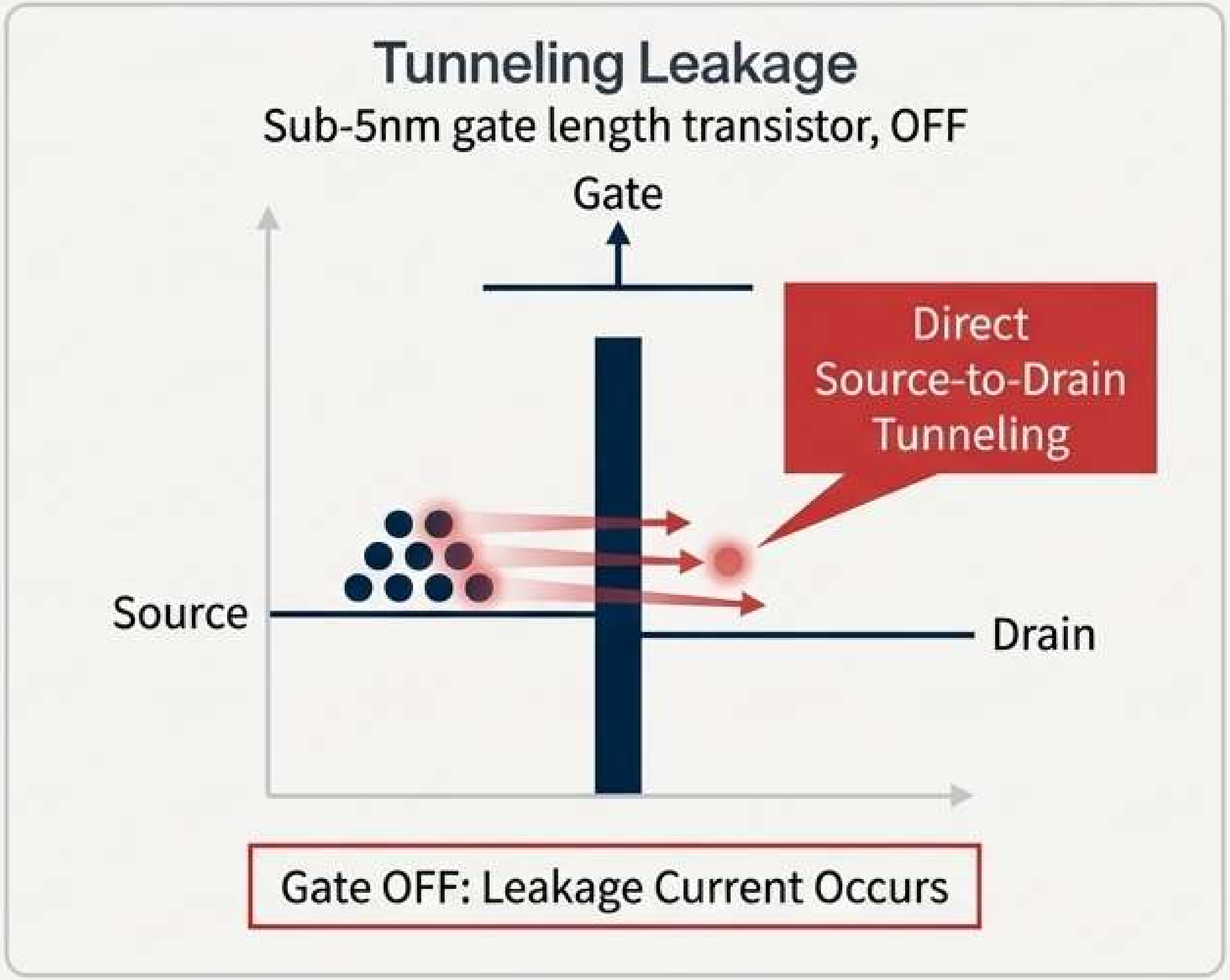
The industry roadmap requires scaling to gate lengths below 5 nanometers to continue performance gains.

A primary physical barrier prevents this scaling in conventional silicon-based silicon-based transistors.

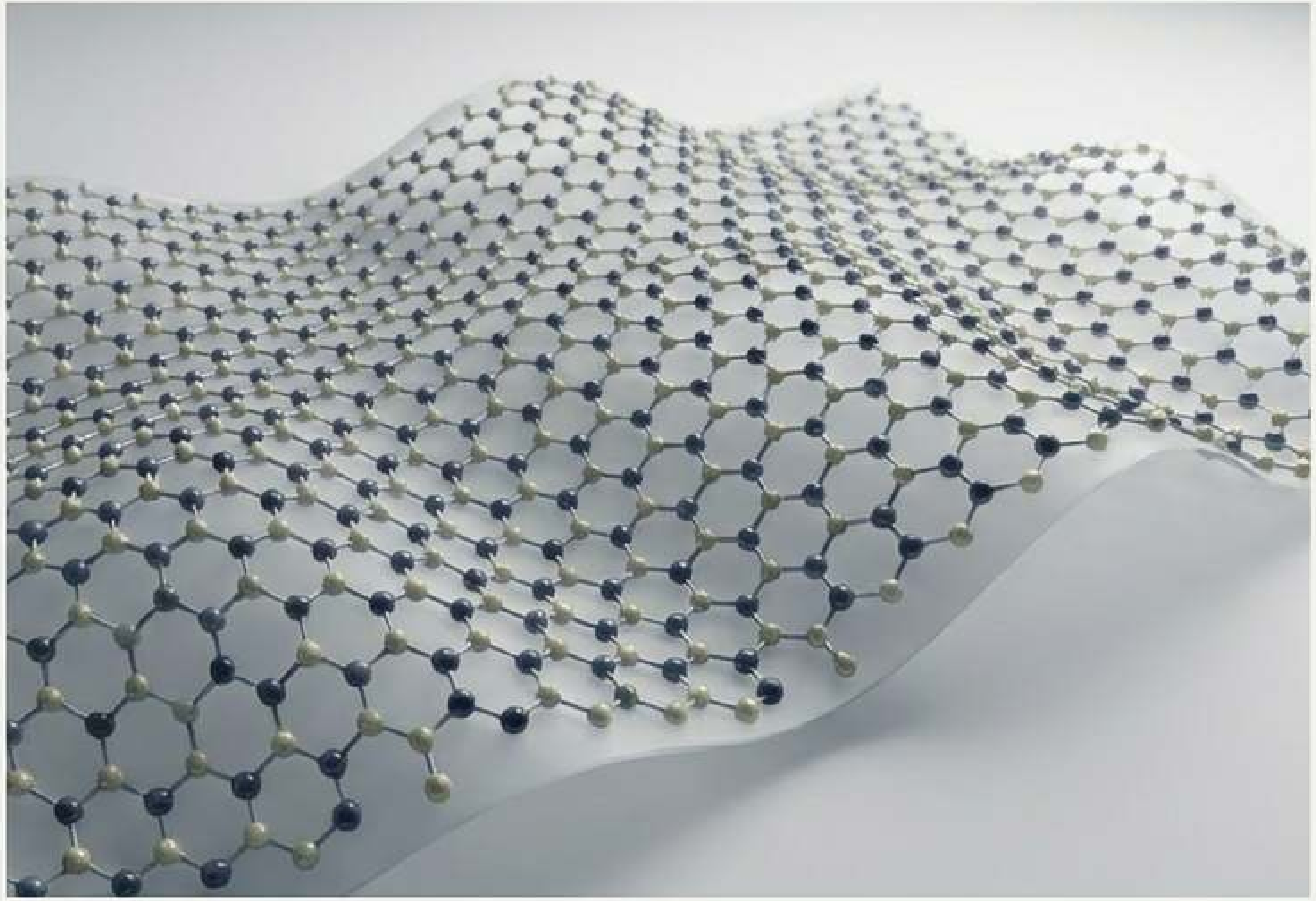
At short gate lengths, direct quantum tunneling creates a 'leaky' transistor.

Ideally, a transistor acts as a perfect switch: current flows only when the gate allows it to pass "above the barrier." In very short gate length devices, electrons begin to flow *through* the barrier even when the transistor is "off." This leakage current fundamentally prevents effective switching and limits further gate length scaling.





2D layered materials offer a theoretical solution to the tunneling problem.



We are exploring two-dimensional semiconductors like Molybdenum Disulfide (MoS_2) for their unique properties that are ideally suited for ultra-short gate length devices.

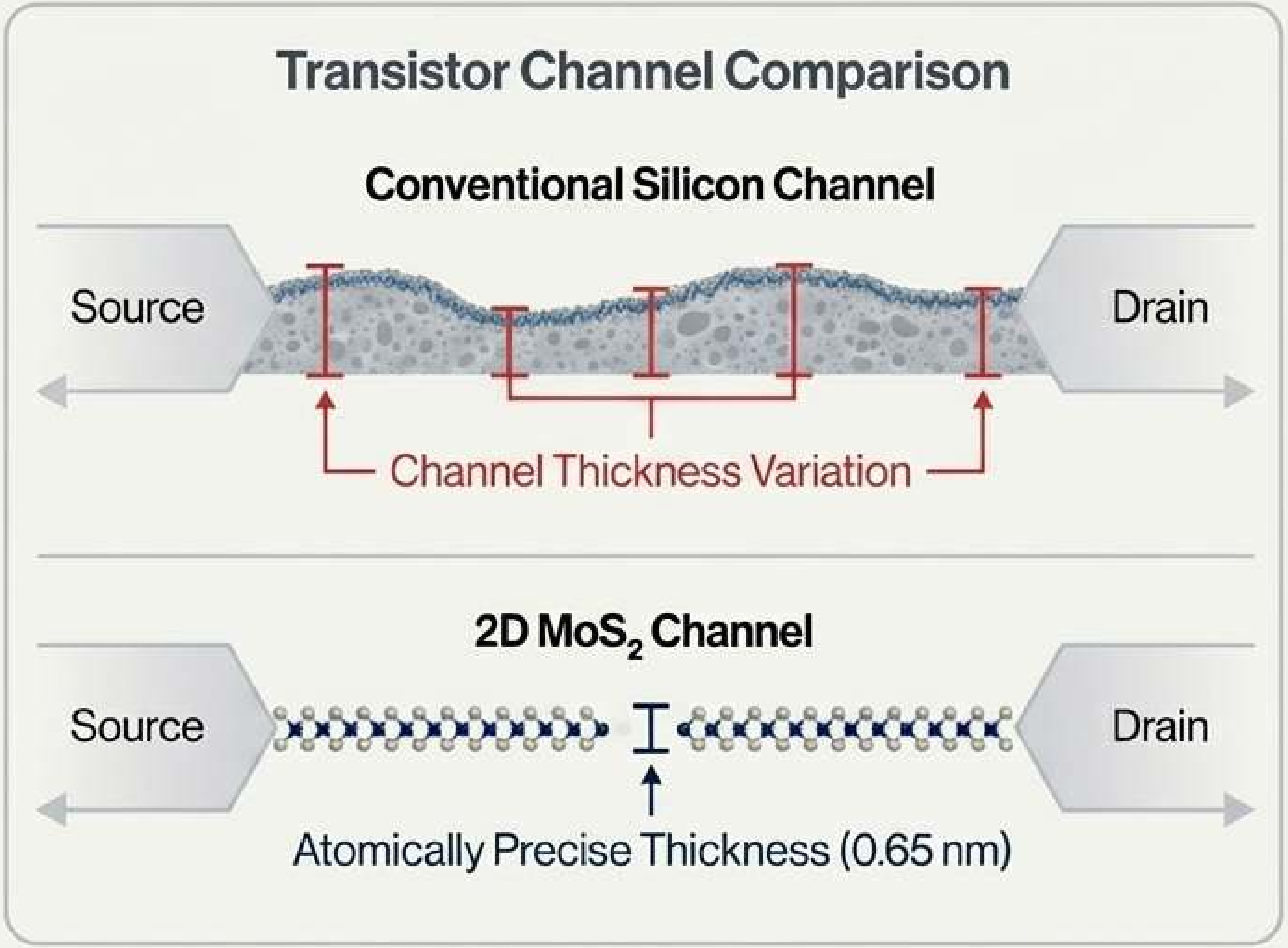
Key Properties to be Explored:

1. Atomic-scale thickness and precision.
2. Higher carrier effective mass.
3. Tunable electronic properties.

Property 1: Atomic precision can eliminate a major source of transistor variability.

- A single layer of MoS_2 is precisely 0.65 nanometers thick.
- It's possible to grow or deposit this single layer with atomic precision across an entire wafer.
- Channel thickness is a significant contributor to variability in conventional transistors.
- By using an atomically precise channel, this component of variability can be drastically reduced.

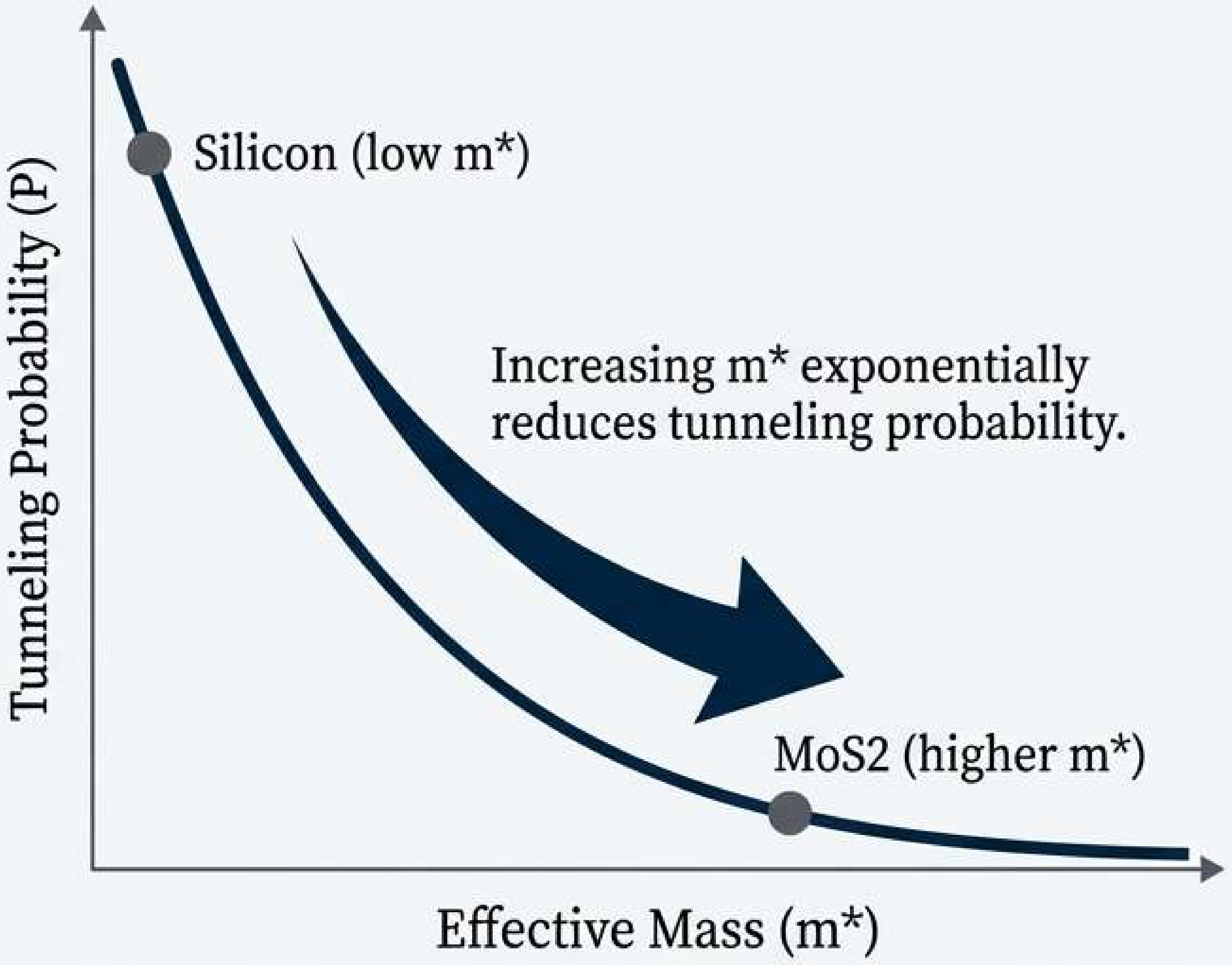
Atomic precision is key to reliable device performance.



Property 2: A higher effective mass physically suppresses electron tunneling.

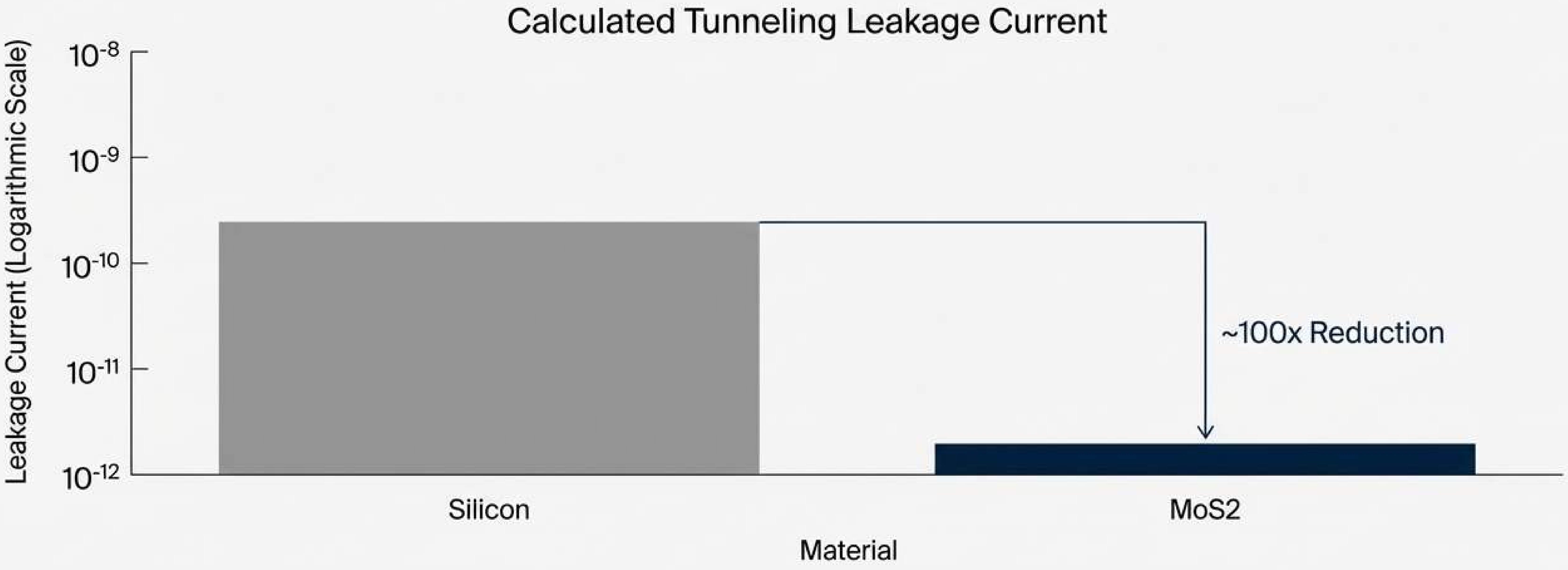
One of the most effective ways to reduce direct source-to-drain tunneling is to increase the effective mass of the charge carriers.

2D semiconductors like MoS2 naturally possess a slightly higher effective mass compared to silicon. This intrinsic property makes it harder for electrons to tunnel through the gate barrier, directly reducing leakage current.



Calculations confirm MoS2 can reduce leakage by several orders of magnitude.

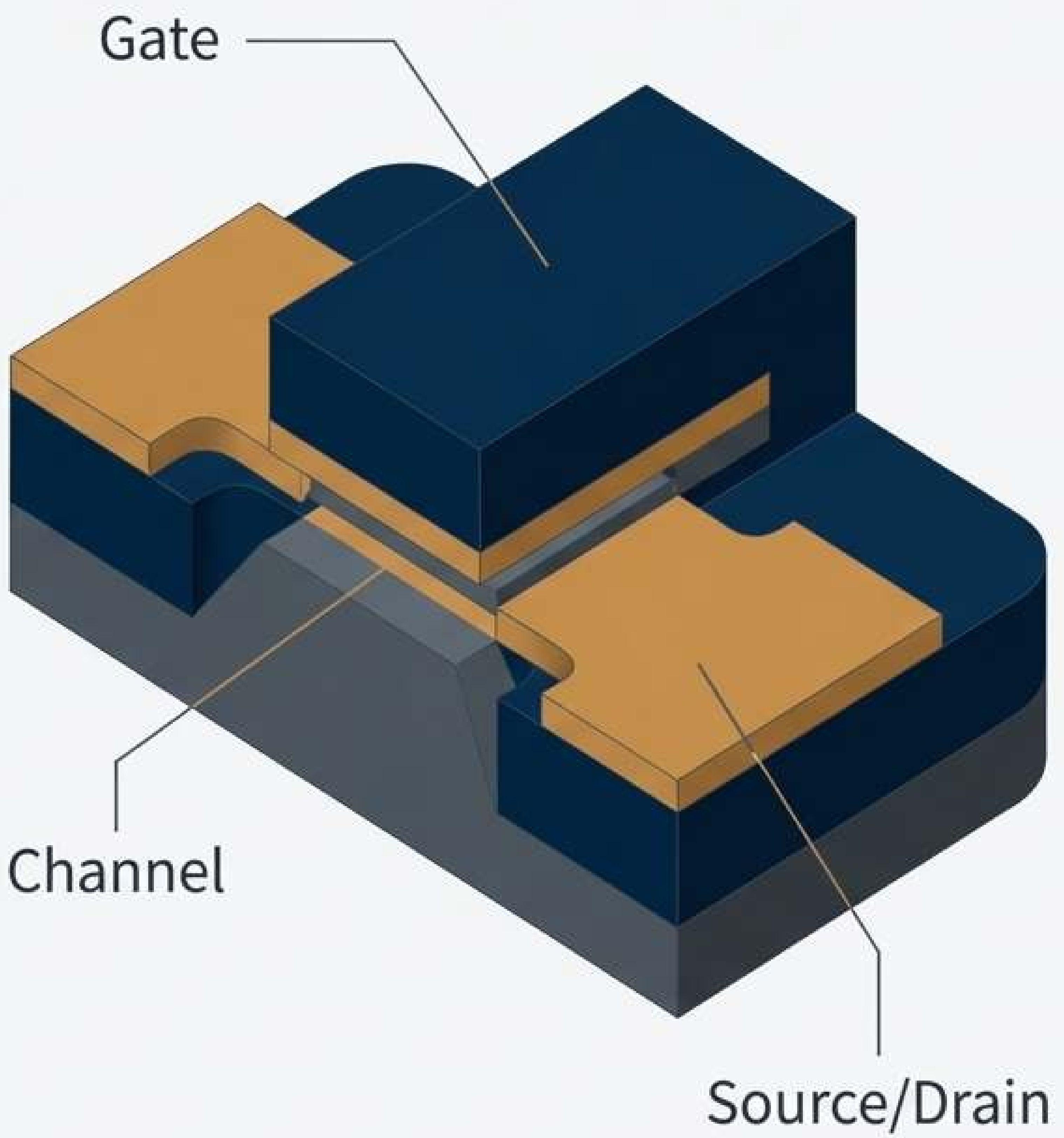
“If we compute the direct source-to-drain tunneling for MoS2, we see a couple of orders of reduction in the direct source leakage component.”



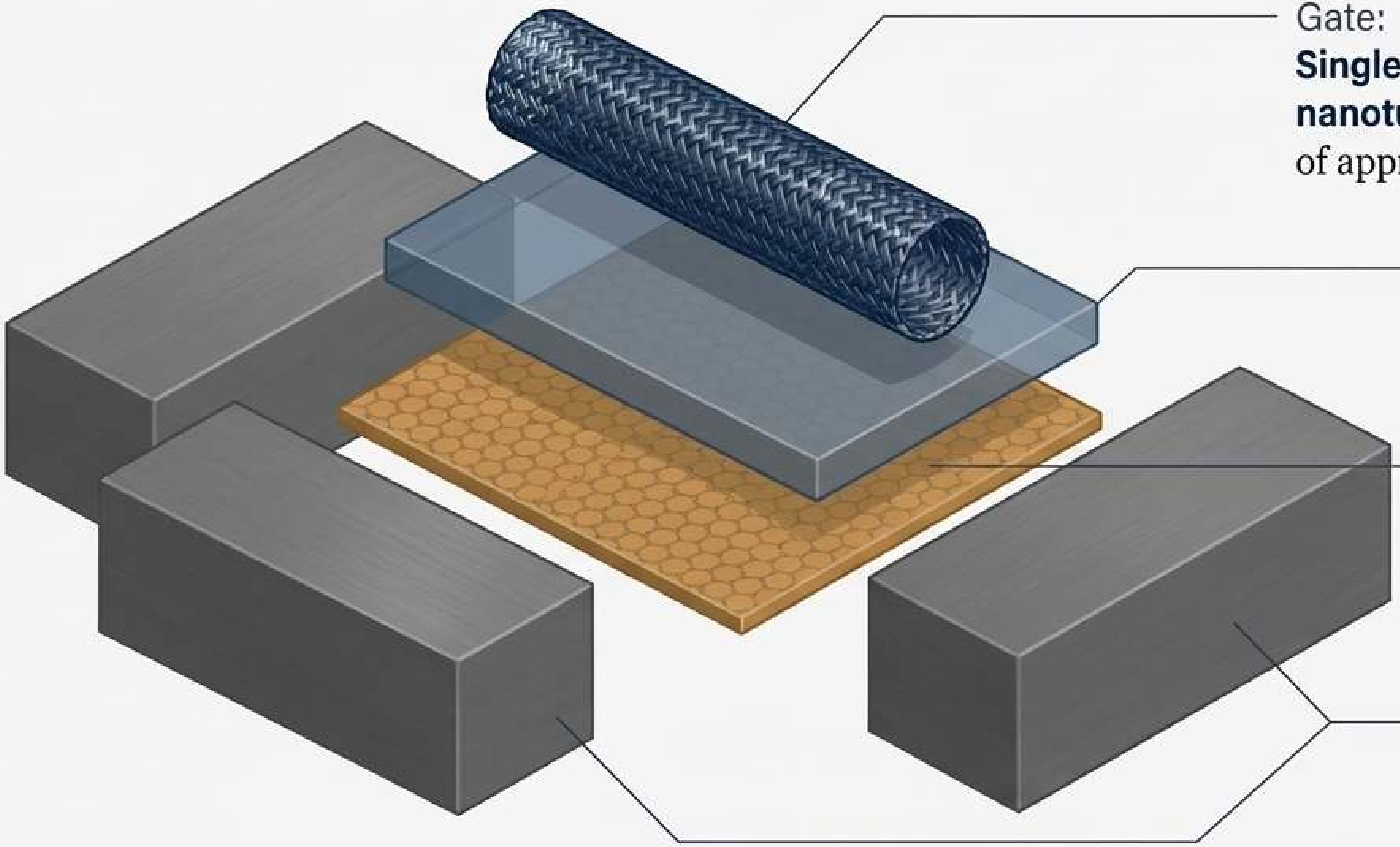
NotebookLM

The hypothesis was tested with a breakthrough demonstration: an MoS2 transistor with a 1-nanometer gate length.

Moving from theoretical advantages to a concrete experimental device.



The device combines novel materials for each key component.



Gate:
Single-walled metallic carbon nanotube (CNT) with a diameter of approximately 1 nanometer.

Gate Oxide:
Zirconium Oxide (ZrO2)

Channel:
Atomically thin **Molybdenum Disulfide (MoS2)**

Contacts:
Source and **Drain** regions

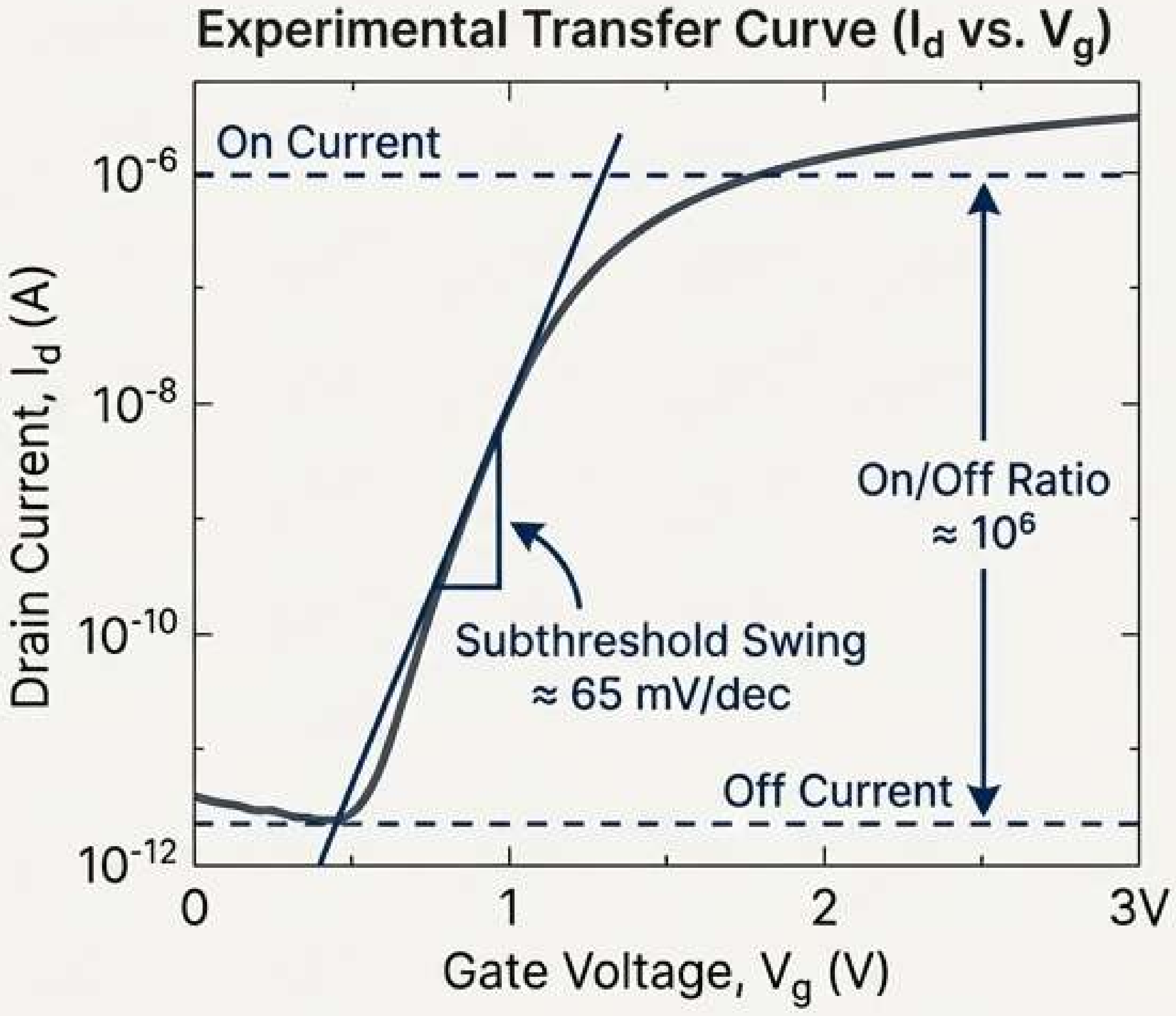
The 1nm device demonstrates near-ideal switching performance at room temperature.

Subthreshold Swing: ~65 mV/decade

This is exceptionally close to the theoretical ideal of ~60 mV/decade at room temperature, indicating a highly efficient switch.

On/Off Current Ratio: ~10^6

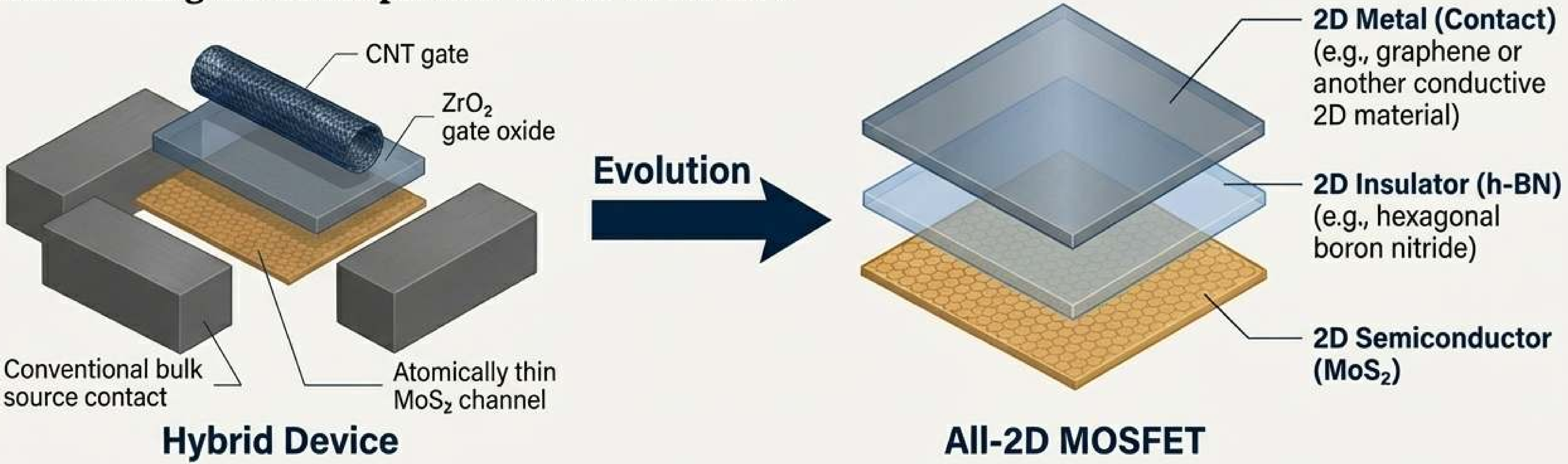
A high on/off ratio confirms very low leakage and a clear distinction between the ‘on’ and ‘off’ states.



Can we push the concept further by constructing a transistor entirely from 2D materials?

The Next Question: What happens if we form a MOSFET where the semiconductor, insulator, and metal contacts are all 2D layered materials?

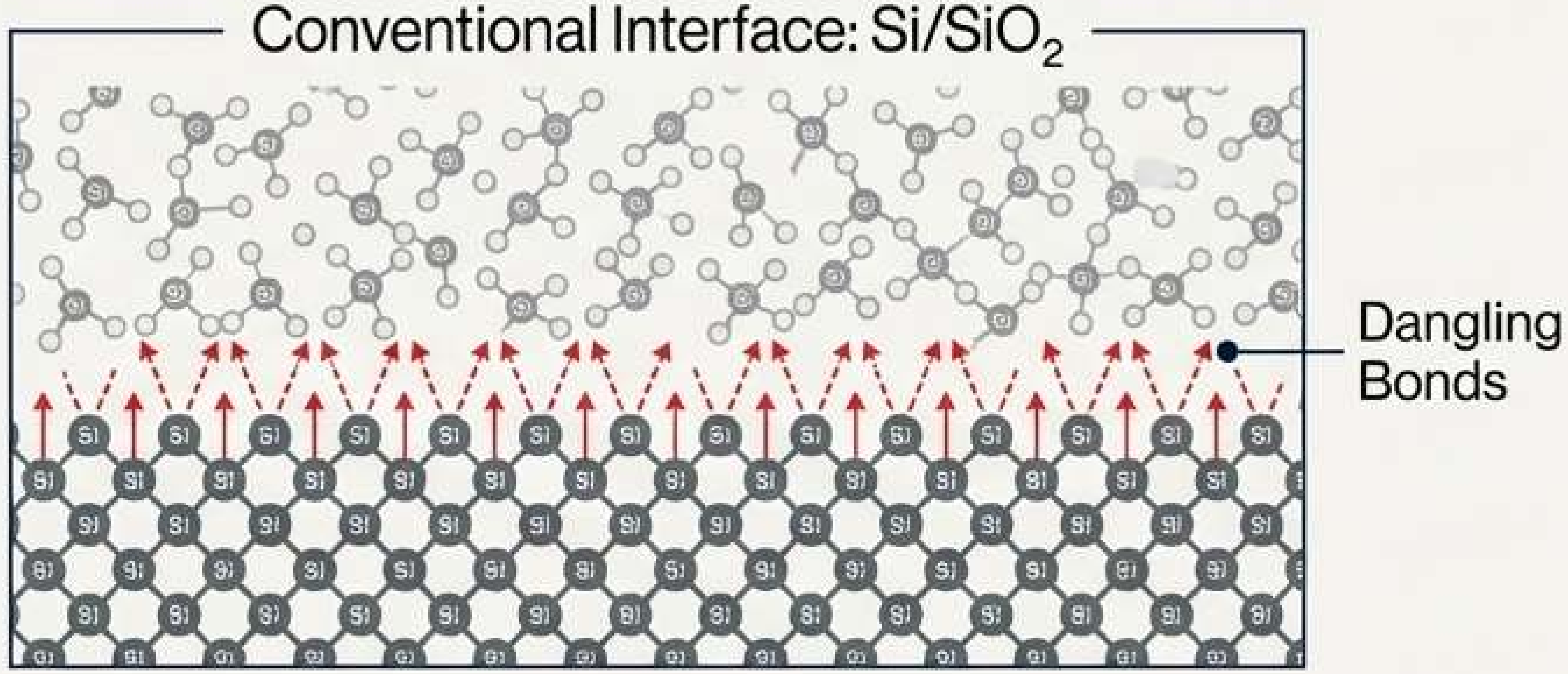
Introducing the Concept: The "All-2D MOSFET".

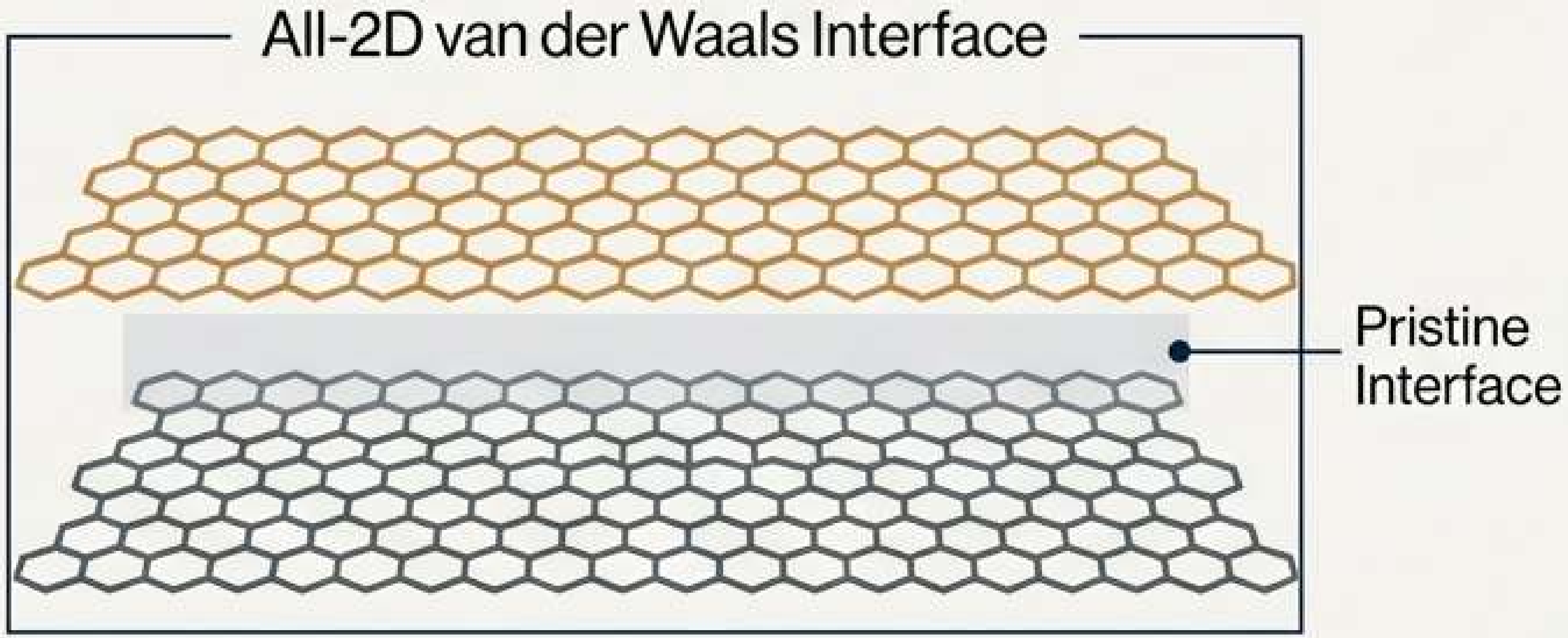


The All-2D architecture creates atomically perfect interfaces

2D materials are atomically thin and precise. Critically, they have have **no dangling bonds** on their surface.

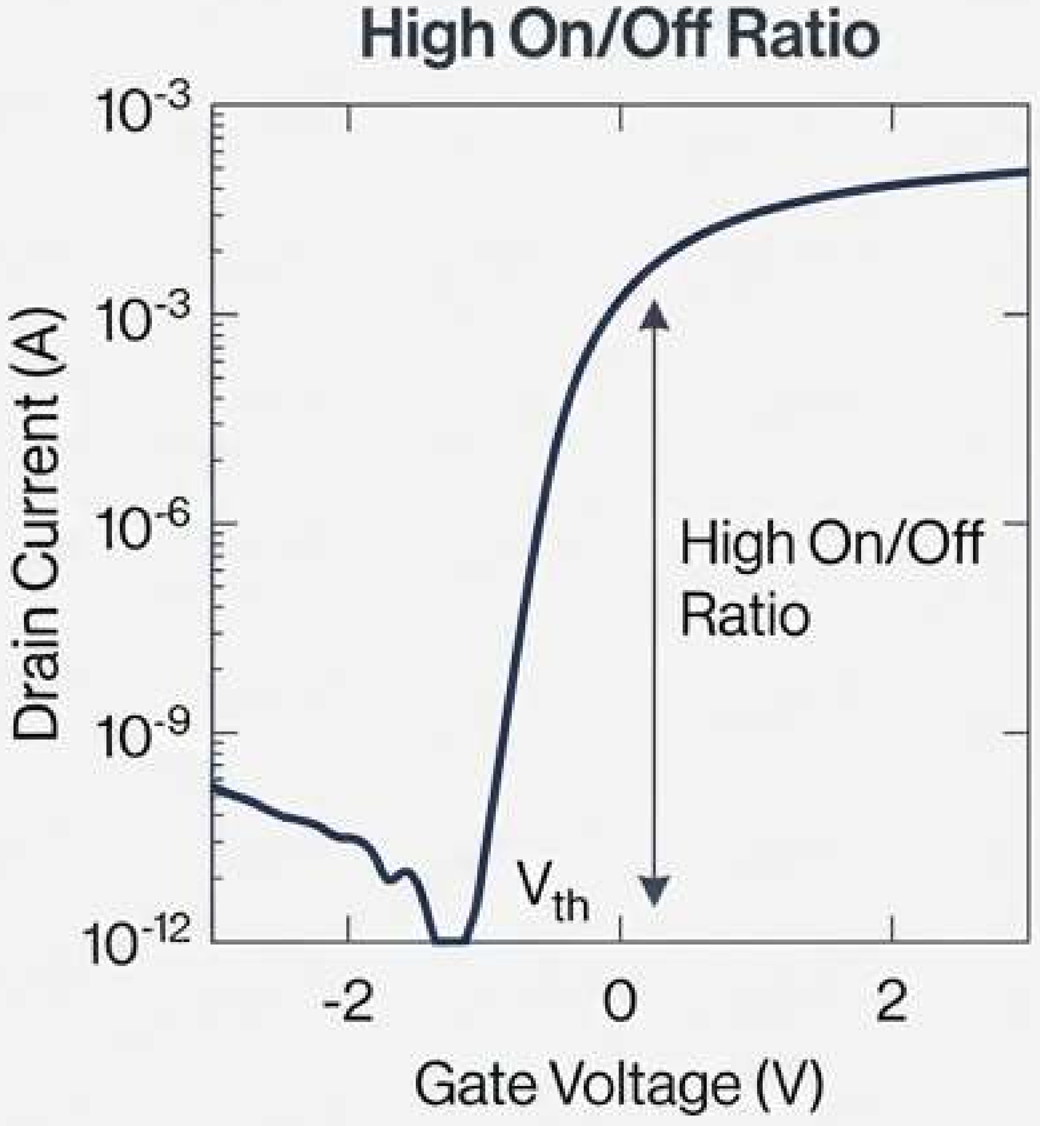
This allows for the creation of van der Waals heterostructures with **pristine, electronically-perfect interfaces** between layers, which is impossible with conventional materials.

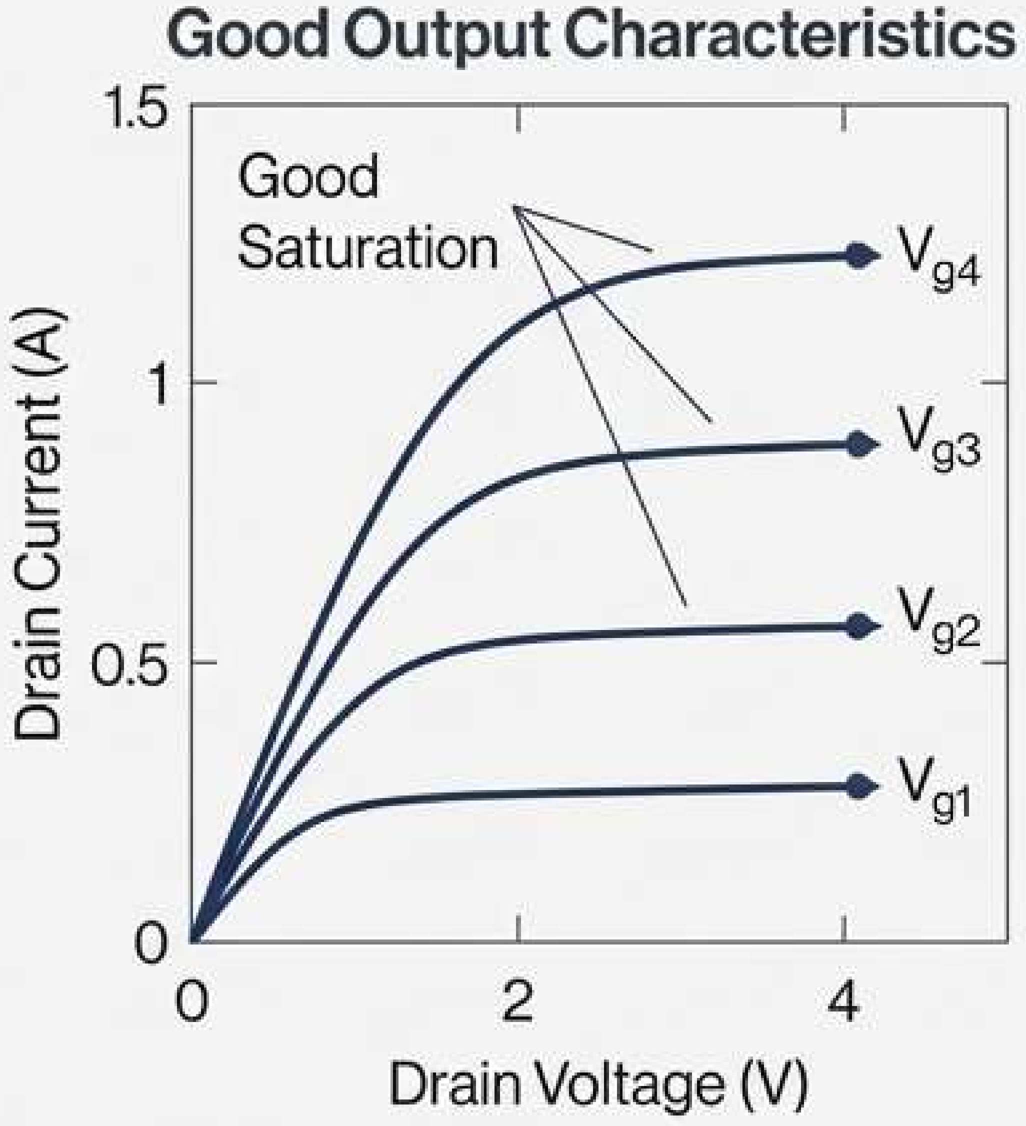




Early demonstrations of the All-2D MOSFET show excellent characteristics.

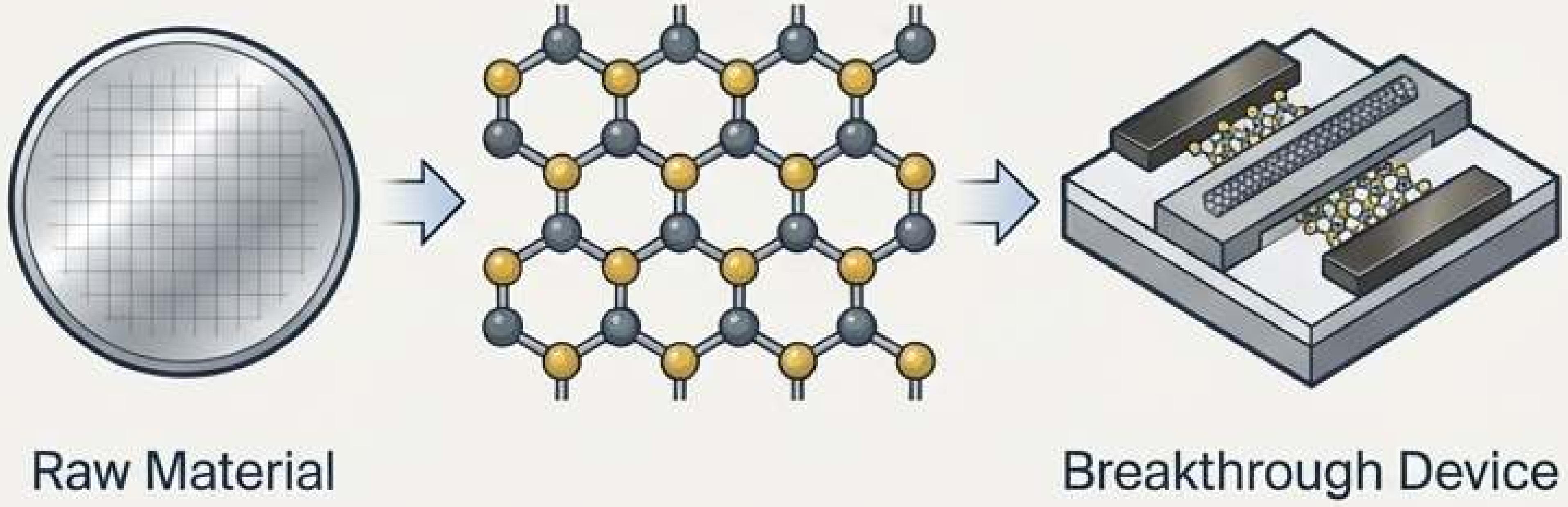
- Achieves a "**very good On-to-Off ratio.**"
- Shows "**good output characteristics.**"
- Reveals interesting behavior in mobility vs. vertical electric field, a key area for further research.





2D materials provide a proven path beyond the physical limits of silicon

- **The Wall:** Silicon scaling is fundamentally limited by quantum tunneling.
- **The Hypothesis:** 2D materials, with their atomic precision and higher effective mass, offered a theoretical solution.
- **The Breakthrough:** A 1nm gate length transistor built with **MoS2** and a **CNT gate** achieved near-ideal switching, proving the hypothesis.
- **The Horizon:** The **All-2D MOSFET architecture** promises even greater performance through atomically perfect interfaces.



The transition to 2D semiconductors represents a new paradigm, enabling the continued advancement of high-performance computing.